

# PIEZOELECTRIC MICROSPEAKER WITH COMPRESSIVE NITRIDE DIAPHRAGM

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## ABSTRACT

A diaphragm-based piezoelectric microspeaker has been fabricated with compressive nitride films, and compared to commercial speakers. The largest sound pressure level (SPL) produced by the fabricated microspeaker is 92 dB (when measured 2 mm away from the microspeaker in open field) at around 3 kHz for 6 V<sub>peak-to-peak</sub> input. The microspeaker produces a comparable sound output as a commercial piezo-ceramic or electrodynamic speaker used in current cellular phones. The key to this success is the usage of a diaphragm that has a very high compressive residual stress, high enough to cause the diaphragm to be wrinkled. And the flatness of the active area in the speaker diaphragm is maintained through a mild tensile stress in the electrode layers, though the non-active area is wrinkled. This way, we produce a large diaphragm deflection (without being hindered by the diaphragm stretching effect) with good control over a flat, active area where the electromechanical transduction is happening.

## INTRODUCTION

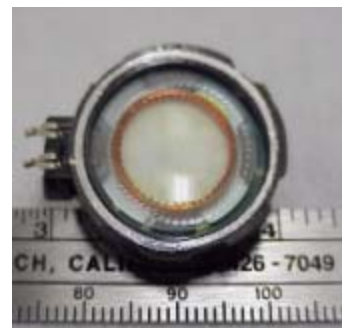
Billions of cellular phones are currently used for personal communications and data transmission, and the demand for more compact size, lightweight, and hi-fidelity audio sound is ever increasing. The manufacturers of the audio components are miniaturizing the microphone and speaker, and also developing a universal device to function as a microphone, microspeaker and buzzer. However, it is very difficult to miniaturize the components without sacrificing their performance characteristics.

MEMS technology has been used to fabricate miniature microphones and microspeakers [1,2,3] on a silicon wafer. This method of fabricating acoustic transducers on silicon wafer has the following advantages over the traditional methods: potentially

low cost due to the batch processing, possibility of integrating transducers and amplifier on a single chip, and size miniaturization. Compared to more popular condenser-type MEMS transducers, piezoelectric MEMS transducers are simpler to fabricate, free from the polarization-voltage requirement, and responsive over a wider dynamic range [4,5,6]. However, piezoelectric MEMS transducer suffers from a relatively low sensitivity in microphone and low output pressure in microspeaker, mainly due to the tensile residual stress in the transducer diaphragm. Compressive stress in the diaphragm can solve this problem, but tends to wrinkle the diaphragm. With a wrinkled diaphragm, it is difficult to control the repeatability of the speaker performance and to have low harmonic distortion.

## DEVICE CONCEPT

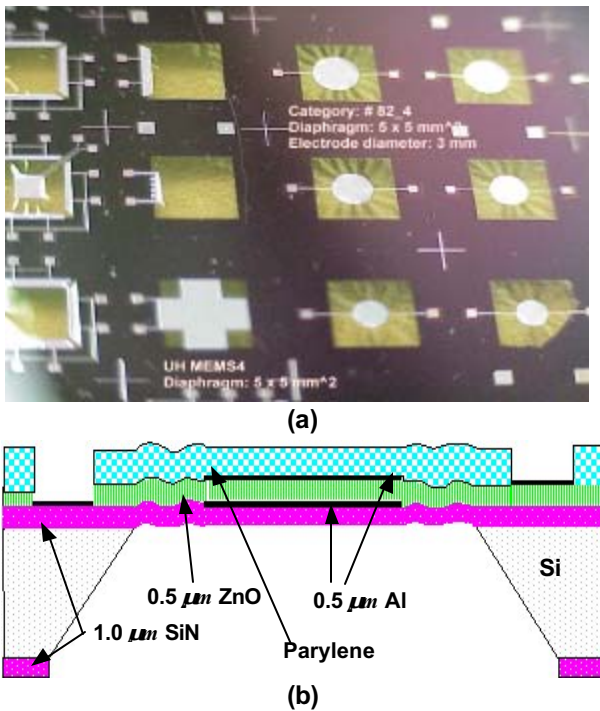
Figure 1 shows a commercial electrodynamic speaker used in European digital mobile phones. The speaker diaphragm is basically composed of two parts: moving area with flat (or dome-shaped) diaphragm and corrugated (or wrinkled) region for large deflection of the moving part.



**Figure 1. Speaker used in European mobile phone (diameter: 23 mm, thickness: 4 mm).**

With MEMS technology, one can create corrugation on the edge of a diaphragm to achieve a large

diaphragm deflection, but its fabrication is complicated and also there is a subtle issue of most of the diaphragm deflection happening at the corrugation (thus not very effective in generating sound with a piezoelectric film). On the other hand, a heavily compressive stressed diaphragm with flatness in the piezoelectrically active area would be easy to fabricate and also be like having distributed corrugation all over the diaphragm. The piezoelectrically active area is maintained flat by mild tensile stress in the electrodes for the active area, while the non-active area is wrinkled due to high compressive stress in the diaphragm, as shown in Fig. 2. The high compressive stress can be obtained by a highly compressive silicon-nitride and/or ZnO film. With the built-in compressive stress in the diaphragm, we can produce a large diaphragm deflection (without being hindered by the diaphragm stretching effect), while keeping a good control over the flat, active area where the electromechanical transduction is happening.

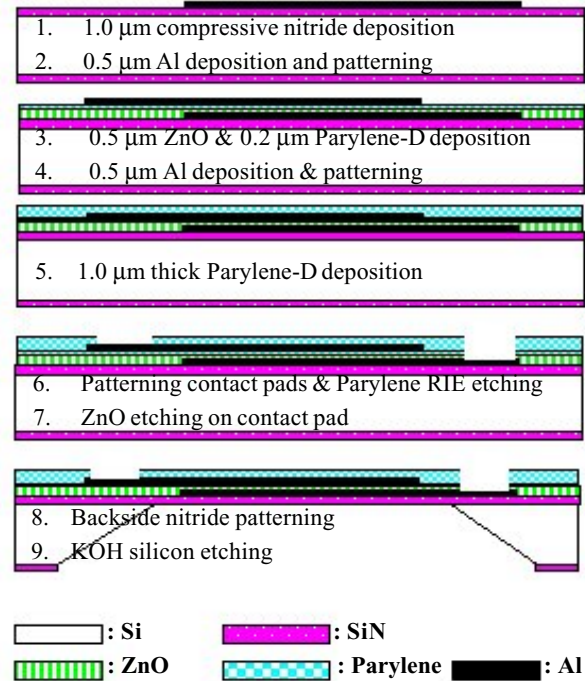


**Figure 2. Piezoelectric microspeaker built on a wrinkled diaphragm; a) photo of fabricated speakers, b) cross-sectional view.**

## DEVICE FABRICATION

Four masks are used in the fabrication process for the piezoelectric microspeaker shown in Figure 3. First, 1  $\mu\text{m}$  thick compressive silicon nitride film is deposited by LPCVD (Low Pressure Chemical Vapor Deposition) system on a silicon wafer,

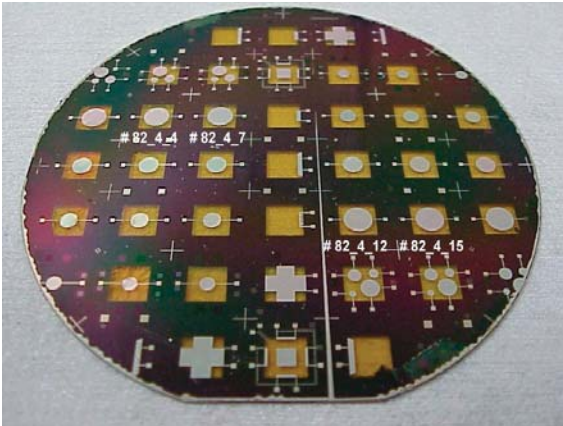
followed by 0.5  $\mu\text{m}$  thick Al film deposition on the wafer front side. After patterning the Al film for the contact pads and the speaker bottom electrodes, 0.5  $\mu\text{m}$  thick piezoelectric ZnO film is deposited by a RF magnetron sputtering system through a two-step deposition technique [7] at 275°C (i.e., using 100 Watts RF power for the first 10 min., and then the usual 400 Watts for the rest of the deposition time). About 0.2  $\mu\text{m}$  thin Parylene-D film is deposited on the front side of the wafer, and patterned with  $\text{O}_2$  Reactive Ion Etching (RIE) to open the contact holes. Then, 0.5  $\mu\text{m}$  thick Al film is deposited and patterned (to form the speaker top electrodes and contact pads) with a wet etchant of  $\text{K}_3\text{Fe}(\text{CN})_6$  and KOH. As the last step on the front side, 1.0  $\mu\text{m}$  thick Parylene-D is deposited (followed by patterning it and the ZnO underneath it) to mechanically strengthen the diaphragm, in order to improve the yield by preventing the diaphragm from breaking during the dicing of the wafer into chips. Since parylene has a low stiffness constant (about a hundred times lower than that of silicon nitride), the diaphragm is mechanically strengthened without affecting the diaphragm stiffness. Finally, the backside silicon nitride is patterned with  $\text{CF}_4$  RIE, and silicon substrate is removed with KOH solution to release the diaphragm [8].



**Figure 3. Fabrication process flow for the piezoelectric microspeaker.**

Figure 4 shows the photo of a fabricated 3" silicon wafer that contains the microspeakers (built on

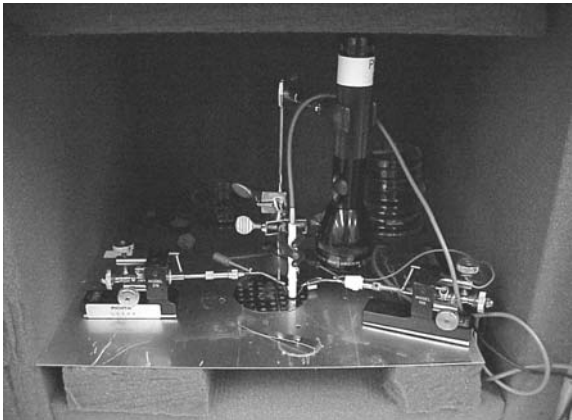
wrinkled diaphragms except the piezoelectrically active regions covered by Al electrodes). We have designed and fabricated various kinds of piezoelectric microspeakers (on a 5 x 5 mm<sup>2</sup> diaphragm) with electrode shapes of circles (2 to 3 mm in diameter), grand cross (1.67 mm wide and with its four edges clamped to silicon), and rectangle (with its wide edge clamped to silicon). The labeling for the tested microspeakers is indicated in Figure 4.



**Figure 4.** Photo taken from the frontside of a completed 3” silicon wafer that contains various acoustic transducers

### EXPERIMENTAL RESULTS

The fabricated microspeaker is tested in an enclosed acoustic chamber (portion of which without the front door is shown in Fig. 5) with a sinusoidal input (6 V<sub>peak-to-peak</sub>). The sound output is measured without an acoustic coupler by a reference microphone (B&K 4135 microphone).



**Figure 5.** Acoustic chamber used to measure the speaker’s sound output pressure.

For comparison, the speakers currently used in

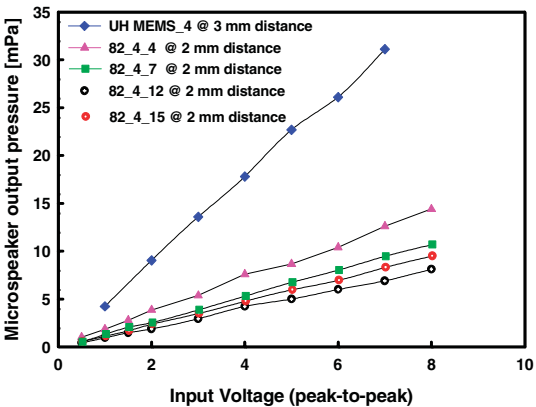
cellular phones (shown in Fig. 6) are tested in the same set up. The speakers named as S-2.0 and S-2.5 are electrodynamic types. The dimensions of the speakers tested are listed in Table 1. The first commercial speaker named as Sonitron is a piezo-ceramic speaker.

**Table 1. Dimensions of the speakers tested (the three commercial ones are round, while the microspeaker is square).**

	[mm]			
	Sonitron	S-2.0	S-2.5	μspeaker
diameter	20.5	18.6	14.1	5×5
thickness	9	3	1.5	0.4



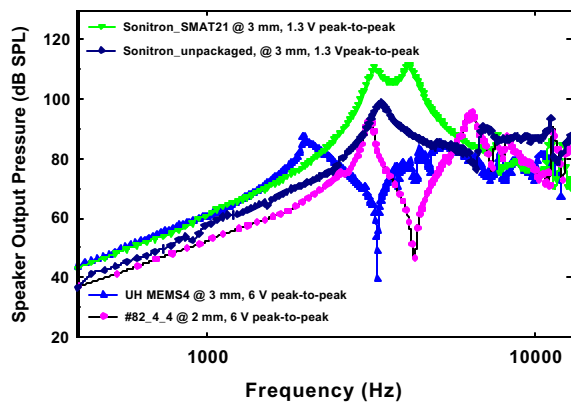
**Figure 6.** Cellular phone speakers tested and compared with the microspeakers: (a) S-2.0 and (b) S-2.5.



**Figure 7.** Microspeaker output pressure versus input voltage measured at 1 kHz (without an acoustic coupler).

As can be seen in Fig. 7 that plots measured sound pressure output versus input voltage, the fabricated microspeakers display good linearity over a wide range. The microspeaker with a grand cross type (labeled as UH MEMS4 in Fig. 2a) produces about 26.1 mPa at 3 mm away from the speaker, while a circular type (# 82\_4\_4 indicated in Fig. 4) produces 10.4 mPa at 2 mm away from the speaker, when driven by a 6.0 V<sub>peak-to-peak</sub>. The frequency responses of the microspeakers are measured between 0.4 and 12 kHz, and are shown in

Fig. 8 along with that of a commercial piezoelectric speaker (the unpackaged speaker means that the upper part of the speaker package is removed). In the frequency range between 0.4 and 1.5 kHz, the microspeakers produce comparable sound pressure as the commercial one albeit with 5 times larger input voltage. The packaged commercial speaker shows a higher sound output between 1.5 and 5 kHz than the microspeakers. But the unpackaged commercial speaker exhibits a significantly reduced output pressure in that frequency span, and the microspeakers are expected to produce higher sound output in that frequency span, when it is properly packaged. Indeed we see in Fig. 9 significant effects that the package produces.



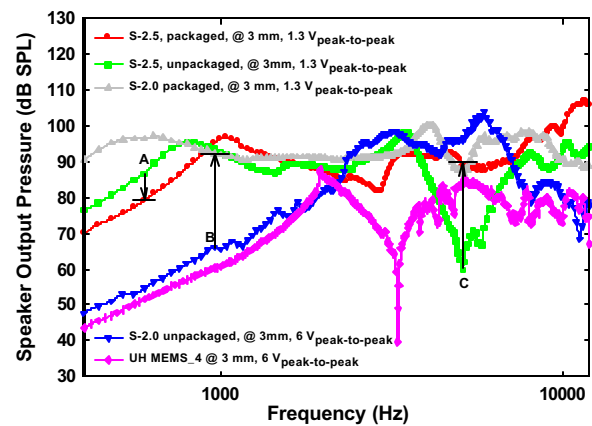
**Figure 8. Speaker output pressure versus frequency between 0.4 and 12 kHz for two microspeakers and one commercial speaker with and without the proper package.**

## CONCLUSION

Piezoelectric microspeakers built on a heavily compressive diaphragm are shown to produce comparable sound output pressure as the bulky, commercial speakers of comparable sizes. The sound output pressure is significantly affected by packaging structures as demonstrated in testing commercial speakers with and without the packaging structures. Thus, the performance of the microspeakers is expected to improve when it is properly packaged.

## ACKNOWLEDGEMENT

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**Figure 9. Speaker output pressure versus frequency between 0.4 and 12 kHz for a microspeaker and two commercial speakers with and without the proper package.**

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